Realism without tears II

Citation for published version:
Isaac, A 2019, 'Realism without tears II: The structuralist implications of sensory physiology', *Studies In History and Philosophy of Science Part A*. https://doi.org/10.1016/j.shpsa.2019.01.003

Digital Object Identifier (DOI):
10.1016/j.shpsa.2019.01.003

Document Version:
Peer reviewed version

Published In:
Studies In History and Philosophy of Science Part A

Realism without Tears II: The Structuralist Implications of Sensory Physiology

Alistair M. C. Isaac

December 4, 2018

1 Introduction

The Doctrine of Specific Nerve Energies has been a fundamental principle in the science of perception since its christening by Johannes Peter Müller in his *Handbuch der Physiologie des Menschen* (1833–40). This Doctrine asserts that we perceive in the first instance the activity of our sensory nerves, not the external properties that stimulate them. This counterintuitive claim rests upon a putative empirical result: the basic qualities of perceptual experience are not determined by, and thus do not reveal the natures of, basic properties in the world. I call this core result the *skeptical conclusion*. This skeptical conclusion exercised enormous influence over both psychology and philosophy in the latter part of the 19th century, but is it still relevant today? Historically, one motivation for resisting the result has been the worry that it implies global skepticism. Part I argued that such skepticism is not in fact an obligatory consequence of the Doctrine, and that Müller himself took it to motivate a form of *epistemic structural realism*. Here, I turn from these primarily exegetical issues to implications for contemporary work in perception and philosophy, arguing for the continued importance of both the Doctrine itself, and its structuralist interpretation, today.

In order to assess the ongoing relevance of the Doctrine's skeptical conclusion, there are three main issues to address. First, insofar as it is understood as an empirical result, is this result still accepted in the contemporary science of perception? Should it turn out that the Doctrine remains scientifically valid, then we must consider its implications for the philosophy of perception. *Prima facie*, the skeptical conclusion directly contradicts both naïve realism, the view that external properties themselves participate in perceptual experience, and those forms of representationalism on which experience transparently reveals features of the world;[1] but more importantly, does it also suggest some positive philosophical moral? Finally, structuralism as an epistemological position is particularly prominent in current philosophy of science, and, as Part I demonstrated, Müller's own structuralism about the epistemology of perception was continuous with his structuralism about the epistemology of science. This motivates a question for the history of philosophy of science, namely whether the Doctrine played any significant role in the historical trajectory of structuralist accounts of scientific knowledge, and whether it should demand the attention of contemporary structural realists.

[1]These views have lately experienced a resurgence; for some pertinent surveys, see Genone (2016), Tye (2014), and Crane and French (2017). Naïve realism about color (e.g. Allen 2016) presents a particularly stark contrast to the view developed here.

Hermann von Helmholtz is a linchpin figure for all three of these issues. Helmholtz was a student of Müller's in Berlin, completing a doctoral dissertation under his supervision in 1842. Subsequently, Helmholtz made major contributions to physiology, psychology, thermodynamics, electromagnetism, and the foundations of geometry, becoming unquestionably the most influential German scientist, if not scientist simpliciter, of the latter half of the 19th century. With regards to the empirical claims of the Doctrine, Helmholtz's pioneering work in the physiology of visual and auditory perception both introduced the most significant breaks with Müller's theory to persist in contemporary psychology, and explicitly reaffirmed the correctness of Müller's Doctrine in its essentials. In popularizing these results, he established the relevance of sensory physiology for epistemology (Cassirer 1950, 4), and as the foremost proponent of a return to Kant involving closer dialog between science and philosophy, Helmholtz may even be considered "one of the principal founders of the discipline we now call philosophy of science" (Friedman 1997, 19). Both directly, through his own writings, and indirectly, through his student Heinrich Hertz, Helmholtz exerted enormous influence on early scientific structuralists such as Cassirer and Schlick.

These then are the answers I will defend to the above questions, each guided in part by the views and influence of Helmholtz. First, as an empirical result, the Doctrine remains as valid today as in the time of Müller. In fact, the methodological presuppositions required to derive its skeptical conclusion play a foundational role in the science of perception, and thus it constitutes an ineliminable tenet of the naturalistic worldview. Consequently, second, any naturalistic philosophy of perception must accept the skeptical claim that the intrinsic qualities of experience are not those of the world. I argue that the most plausible maneuver to save realism in the face of this result is to adopt some form of structural realism. Finally, it is easy to demonstrate that the Doctrine played some significant role in the early history of scientific structuralism, insofar as it motivated Helmholtz, who himself inspired a number of early 20th century structuralists. While the facts of perception no longer play an evidentiary role for most modern philosophers of science, I argue that sensory physiology may still serve as a valuable exemplar for contemporary structural realisms.

2 The Doctrine Today

The *skeptical conclusion* of the Doctrine of Specific Nerve Energies asserts that the basic qualities of perceptual experience are not determined by, and thus do not reveal the natures of, basic properties in the world. Part I argued that this conclusion follows from empirical results provided one assumes three methodological principles. The empirical results concern the success of stimuli "inadequate" (atypical) to an organ (e.g. pressure on the eyeball) in generating that organ's characteristic sensory experiences (a flash of color). The results themselves are incontrovertible, comprising frequently performed experiments, easily checkable demonstrations, and publicly accessible facts. Müller moves beyond the incontrovertible to the contentious when he presents these results as a double dissociation between external causes and perceptual effects: the same cause may incite different effects when applied to the nerves of different sensory organs, while the same sensory effect may be induced by radically different physical causes. From this double dissociation, it follows immediately that sensory qualities are not identical to those of their causes, and consequently that perceived qualities are not directly identifiable with the properties of external objects.

I take there to be two contentious aspects to Müller's argument. First, Müller's conclusion that radically different physical causes may produce the "same" sensory effect requires some test of sameness of sensation type.[2] If sensations induced by adequate and inadequate stimuli are not sufficiently similar, then the skeptical conclusion does not follow, as the realist may treat the two types of sensation as different in epistemic status. For instance, if some characteristic is shared by all tastes due to adequate stimuli, such as those of chocolate cake and beetroot, but not found in those due to inadequate stimuli, e.g. the "taste" of a live battery on the tongue, then the realist may coherently insist that the well-defined category of adequate taste sensations directly reveals external properties, while still acknowledging that experiences due to inadequate stimuli, such as the battery "taste," are opaque to the nature of their causes (Gibson 1986, 246). I take Müller's argument here to implicitly rely on two methodological principles. The *unitary correspondence principle* legitimates inferences from nervous activity at the periphery to downstream functional effects. The *principle of comparability* legitimates phenomenological claims about whether two perceptual experiences are of the same type. Since these two principles are vindicated in contemporary perceptual science, I take the double dissociation result to remain valid today.

Nevertheless, a prominent heterodox approach argues the atypical sensory phenomena that serve as the empirical basis for the Doctrine are not relevant to a theory of perception proper. If this argument is correct, and only those experiences induced by adequate stimuli are legitimate evidence in perceptual science, then the double dissociation result, and so also the skeptical conclusion, may be avoided. This line of argument was prominently advanced by ecological psychologist J. J. Gibson, who in turn has led many naturalistically-inclined philosophers of perception to rest comfortable with the claim that we directly perceive distal properties of the world. Müller explicitly addresses this worry when he argues that atypical sensory situations, what he calls "subjective phenomena," constitute the primary evidence for perceptual science—his third methodological principle (Part I, Section 3.2). I defend Müller's perspective, arguing that Gibson's considerations do not undermine the evidential import of atypical sensory phenomena, nor the empirical status of the Doctrine, although they do have implications for the epistemology of perception, that are addressed further below (Section 3.2).

2.1 The Unitary Correspondence Principle

One argument to the conclusion that radically different stimuli (light, pressure, electric shock) may all produce the "same" type of sensation (e.g. a flash of color) rests on purely physiological considerations. So long as their connectivity remains unchanged, nerve fibers in the lab behave the same regardless of the manner of stimulation; consequently, we may safely assume the same sensory effect follows no matter how a sensory nerve is stimulated, whether by typical or atypical stimuli. I call this the

> *Unitary Correspondence Principle* – each (sensory) nerve fibre projects to a distinct location in the brain and, when stimulated, always produces the same distinct effect.

Müller took something like this principle to serve as a necessary precondition for a science of neurophysiology, and employs it in arguing for the skeptical conclusion.[3] In assessing the UCP today, we must be

[2] The other direction—from same physical cause to different sensory effects—is not contentious, because a single, token-identical stimulus may induce multiple sensory effects, e.g. when the very same ray of light induces warmth on the skin and brightness at the eye.

[3] An inverse UCP applies to motor nerves, namely same cerebral stimulation implies same motor effect at the periphery. Mülller uses this symmetry, and the analogy between motor and sensory nerves it establishes, extensively in reasoning about the nervous system (1:617/612*f*). He takes symmetry to follow from the Bell-Magendie Law: the anterior of the spine

careful about the type of "effect" at issue. On the one hand, the idea that the same *consciously accessible* effect follows whenever a particular nerve is stimulated is demonstrably false, as illustrated for instance by the Necker cube, which changes in perceptible properties even as the incoming stimulus remains constant. Conversely, if we understand the effects at issue as subpersonal and functionally defined, then this principle may be found enshrined in the contemporary information processing approach to neuroscience.

The role of the UCP in Müller's argument has been muddied by debate over how to interpret the "energies" alluded to by the Doctrine of Specific Nerve Energies. If these are special powers, fluids, or activities distinctive of nerves associated with a particular sensory organ, as Müller sometimes seems to indicate, then they could indeed play the relevant inferential role: a distinct, sensation-inducing physico-chemical property, shared across all and only nerves of a particular sense modality, would license the inference from the fact that some nerve of that modality has been stimulated to the conclusion that the resulting sensation is of the same type as any other within the modality, no matter the nature of the stimulus. Nevertheless, contemporary neuroscience does not recognize such special energies, and so it would be damning if the reasoning of the Doctrine rested on this assumption. The 19th century followers of Müller were split between this ontologically robust, physico-chemical interpretation of nerve energies and a deflationary, informational reading, more in line with contemporary views. On the deflationary side may be counted Müller's doctoral students Helmholtz and Emil du Bois-Reymond; on the physico-chemical, avowed intellectual disciples of Müller, Ernst Mach and Ewald Hering. Helmholtz and du Bois-Reymond placed little emphasis on Müller's talk of "energies," emphasizing instead the importance of the location in the brain to which sensory fibres project for determining phenomenal quality.[4] In contrast, Mach and Hering argued that only an ontological interpretation of the specific nerve energies as distinct substances could perform the relevant explanatory role, i.e. explain *why* the qualities of the senses differ, and that this crucial insight of Müller's had been ignored or "suppressed even by [his] own disciples" (Hering 1913, 28; cf. Mach 1896 [1885], v–vi, 193; Banks 2000, 106*f*).

Part I argued that Müller himself was not committed to any specific ontology of nerve "energies," but rather that "energy" serves as a placeholder for unreduced, lawlike behavior. Law VII of the Doctrine explicitly asserts ignorance about whether it is a special property of the nerves, or merely the brain region to which they project, that determines sensory quality (Part I, Section 3.1). Müller's physiological argument to the skeptical conclusion does not rest, then, on any particular theory of nervous activity. Rather, Müller's reasoning draws on his methodological commitments. He recognized the need for a principle upon which to ground inferences about the physiological structure of the nervous system from

contains only motor nerves and the posterior only sensory nerves; correspondingly, stimulation of nerves from the anterior produces effects in the periphery (motor contraction), while stimulation of nerves from the posterior produces effects of (apparent) sensation (typically of pain) in vivisection experiments. Since motor nerves have easily observable consequences (muscle contractions), one can confirm experimentally that the same effect is produced whether they are stimulated by mechanical, chemical, or electrical means: a motor nerve projecting to a frog's thigh muscle produces a contraction whether stimulated by scraping with a pin, shocking with electricity, applying a candle flame, or pouring on alkali. The ease with which this unitary correspondence can be observed in the motor case provides, for Müller, support for the UCP as it applies to sensory nerves.

[4]Emil du Bois-Reymond is perhaps most famous as the discoverer of the nerve action potential, work which, while advancing our understanding of neural anatomy, also undermines the idea that nerves of different modalities have distinctive characteristics—rather, for du Bois-Reymond, all nervous activity is fundamentally electrical. Nevertheless, he explicitly endorsed Müller's Doctrine, identifying distinctive sensory qualities with their associated *Hirnprovinzen*, or brain regions (1874, 19). Helmholtz's *Zeichen*, or "sign," theory of nervous activity is discussed further below (Section 3.2); on this view, the functional role that emerges from learned associations determines the character of sensation. While it is strictly anachronistic to call these "information processing" views, they nevertheless presage the modern commitment to explain nervous activity in terms of the transmission and transformation of symbols, distinguished by functional role rather than intrinsic type.

experiments at the periphery, arguing that such inferences would be impossible, and thus also a science of nervous activity, unless one denies that nerve fibres anastomose, i.e. combine into larger branches as blood vessels do.

> If . . . the primitive fibres anastomose with each other in their course within the small fasciculi, . . . then the cerebral extremity of a nervous fibril will be in relation with very many peripheral points . . . no local impression on a single definite point would be perceived by the brain; for the sensation of a single point evidently depends on the impression being conveyed by means of a single fibre to a single point of the sensorium . . . The possibility of our establishing an accurate theory of the action of the nerves rests wholly on the question of the primitive nervous fibres anastomosing, or not. (1:606/600–1)

The very possibility of our "establishing an accurate theory" of nervous activity requires that anastomosis be false. Assuming no anastomosis occurs allows us to draw inferences about the functional role played by nerves in connecting the periphery of the body with the brain. Thus, the first clause of the UCP makes an assertion about the structure of the nervous system, while the second adds the inference-licensing claim that same (point) stimulation implies same effect. If we adopt these assumptions, then the double dissociation follows: that the very same nerve fiber can be stimulated by both a battery and chocolate cake implies that the very same (type of) effect is generated by both battery and cake, namely a taste.

This second clause of the UCP is the one that historically has been a matter of debate. If by "taste" one means a consciously accessible sensory quality, then the arguments of the gestalt psychologists seem to show this principle, which they dubbed the "constancy hypothesis," is incorrect. They demonstrated that point stimulations do not always generate the same sensory effect by drawing attention to phenomena where point stimulations do not vary, yet sensory experience does, such as the spontaneous reversals that occur while viewing a Rubin vase or Necker cube. Historically, the way to explain such phenomena within the scope of the constancy hypothesis was by appeal to "unnoticed" primitive sensations that presumedly stay constant across these reversals, and may be recovered through training and reflection. Köhler (1971 [1913]) demonstrated this strategy to be methodologically corrupt—any such theory is trivially unfalsifiable, as apparent counterevidence may be summarily rejected as the result of insufficient training or incompetent introspection (cf. Section 3.1).

However, we must be careful here to distinguish the claim that stimulation of a nerve fiber always produces the same effect, from the stronger assertion that this effect corresponds directly to a sensation. If one is interested in the functional role of subpersonal signals in sensory circuits, as is physiologist Müller, then the weaker claim is sufficient to show the dissociation between external cause and sensory effect. No matter how different the perceived "taste" of batteries and chocolate cake, insofar as they result from stimulation of the same set of nerves, they must be treated as playing analogous informational roles within the neural economy, on pain of abandoning neurophysiology as a science. Moreover, this subpersonal reading of the UCP is essentially the basic tenet of the contemporary, "information processing" view: neural signals participate in complex computations, but the nature of these computations is determined wholely by local interactions; the upstream circumstances that produced the signal are irrelevant, only the presence (or not) of the signal matters.

This line of reasoning has the desired implication, that sensations due to adequate and inadequate stimuli are of the same epistemically-relevant type, only if one antecedently accepts that perceptual content is grounded in, or reduces to, the information content of the subvening neural processes; in other words, that personal-level knowledge attributions inherit their epistemic status from subpersonal phenomena. For those who reject this reductionist project, a further argument is needed that the experiences induced by inadequate stimuli are indeed of the same *phenomenological* type as those due to adequate stimuli. Without this further argument, the double dissociation between sensations and stimuli, and thus the skeptical conclusion, need not follow. While the needed additional principle is not explicitly articulated by Müller, it nevertheless may be found as a fundamental methodological principle in the practice of psychophysics.

2.2 The Principle of Comparability

Psychophysics measures the degrees of similarity and difference between personal-level, perceptual attributes, and the extent to which these similarities and differences reflect physically specifiable features of the stimulus. When studying color, for instance, stimuli may be colored lights, the spectral properties of which can be precisely specified in physical terms. The output of an experiment is some form of behavior that reveals a perceptual judgment, for instance, identifying two lights as "the same" in perceived color, or ordering lights such that each is more similar in perceived color to its neighbors than to any others. Several kinds of theoretical model may be derived from experiments such as this. On the one hand, one can model internal relations between similar perceptual attributes, such as the familiar arrangement of perceivable colors into a three-dimensional color solid. On the other hand, one may measure systematic discrepancies between perceived qualities and their physical correlates—in the case of color, for instance, the identification of metamers, physically different but perceptually indistinguishable color stimuli. Analogous methods may be used to model any perceptual property: pitch, weight, shape, smell, etc. (Stevens 1975; Clark 1993).

The core assumption behind these methods is that comparisons may be made with respect to the sensory quality at issue. If subjects cannot make such comparisons, or if they attempt to do so, yet produce inconsistent groupings or orderings, then the presumed sensory quality is not real. Consider, for instance, the experience of "tonal volume," or the perceived size or spatial extent of a sound (not to be confused with "loudness," the perceived intensity). Since simple auditory stimuli such as sine waves are defined by just two parameters, frequency and amplitude, it would be surprising if they triggered three distinct perceptual attributes: pitch, loudness, *and* volume. The debate on whether tonal volume is indeed a real perceptual attribute turned largely on the question of whether subjects could make consistent comparisons of stimuli with respect to volume. Some labs reported subjects making consistent judgments of volume, ordering stimuli with respect to perceived volume in the same way as the experiment was repeated. Other labs claimed subjects were confused by the instruction to attend to spatial extent of auditory stimuli and were unable to compare different sounds with respect to volume at all (Isaac 2017).

I take it that the methods of psychophysics are coherent only on assumption of the

> *Principle of Comparability* – two experiences are of the same perceptual type if and only if comparisons between them of sameness, difference, and degree of similarity may be made consistently.

The example of tonal volume illustrates how this principle may be applied to determine whether two auditory experiences both instantiate the attribute of spatial extent. This method may be extended to any case where one wonders whether two stimuli produce sensations of the same type. For instance, is "volume" perceived in the auditory modality the "same" sensory quality as volume perceived visually? Psychophysics offers a principled means to answer this question, by asking subjects to make comparisons of stimuli across the two domains; for instance: is this (auditorily presented) tone perceived as larger or smaller in volume than this (visually presented) box? If subjects are able to make such judgments consistently, then the qualities are of the same type.

If we accept the Principle of Comparability, the question whether perceived qualities due to adequate stimuli and those due to inadequate stimuli are the same in type is strictly an empirical one. Is, for instance, the "color" of afterimages the same type of property as the color of experiences due to ordinary stimuli? If it is, then subjects should be able to make comparisons (for instance, matches) with respect to color between both types of experience. As it happens, such comparisons are indeed possible. Most psychophysical experiments simply assume that afterimages have "color" of the same sort as we perceive from adequate stimuli, since they rely on subject reports of the color of afterimages using the same vocabulary, i.e. my consistent ability to identify this afterimage as yellow and that as green demonstrates that yellow and green are appropriate perceptual categories for analyzing them. Some experiments, however, do rely on pure behavioral matching, for instance a study by Lier, Vergeer, and Anstis (2009), where subjects matched adjustable sections of their monitor to perceived afterimages, thereby illustrating that afterimage color and color due to adequate stimuli are indeed, from a psychophysical standpoint, the same type of property.

The principle of comparability has the advantage of operationalizing the question of whether, given any percept due to an inadequate stimulus, it is indeed of the same type as some set of percepts due to adequate stimuli. Do the kinds of unusually induced percepts that serves as evidence for the Doctrine pass this test? Unfortunately, experiments of the sort described for afterimages are either rare, or non-existent, for some of the examples Müller found especially useful. Occasionally, this is due to practical or ethical impediments. For instance, the claim that all sensory modalities may be stimulated by electrical current is due to a set of late 18th century experiments by Volta and Ritter, in which the two investigators independently shocked their sensory organs and reported their experiences. In the case of Ritter, there is evidence that these experiments contributed to illness and early death, casting doubt on the wisdom of reproducing them. Nevertheless, for many of the examples that Müller appeals to, formal experiment seems unnecessary for establishing comparability. The warmth of sunlight on the skin is patently similar in quality to warmth from friction; ringing due to tinnitus is clearly similar to, and often mistaken for, distally caused ringings; etc.

So, the phenomenological claim that two sensory qualities are of the same type may be established by testing whether they are consistently comparable. This is a foundational assumption of psychophysics, as it continues to be practiced today. We should accept the unitary correspondence principle and the principle of comparability because they are presuppositions of fruitful research programs for studying the senses—to deny them is to reject neurophysiology and psychophysics as sources of empirical evidence. Granting these two principles, the double dissociation between distal causes and sensory effects follows quickly from the data, and upon its heels, the Doctrine's skeptical conclusion.

Nevertheless, a prominent alternative to mainstream perceptual science rejects both reductionism and the relevance of traditional psychophysics to phenomenology, *a fortiori* epistemology. Proponents of this approach explicitly argue that it avoids the skeptical conclusion, allowing for a realism-friendly science of perception. Müller's final methodological principle speaks to their concerns.

2.3 "Subjective" Phenomena

The first two methodological principles ground inferences in neurophysiology and psychophysics respectively. The third principle concerns rather the evidential basis for the science of perception; Müller asserts that "'subjective' phenomena" reveal the "true" activities of the senses, i.e. provide the evidence that grounds any adequate perceptual science (Part 1, Section 3.2). While mainstream psychophysics has sided with Müller on this point, the ecological psychology of J. J. Gibson explicitly rejects it, arguing Müller's subjective phenomena are of only secondary importance, relevant perhaps to neuroscience, but not to a theory of perception proper. Here, I defend Müller's evidential claim against this critique, arguing subjective phenomena are fundamental to perceptual science—consequently, psychophysics investigates perception proper and, by the principle of comparability, the skeptical conclusion constitutes an empirical result. This is a methodological point, however, and does not necessarily undermine Gibson's epistemological position, which we will return to below (Section 3.2).

By "subjective" phenomena, Müller means empirical effects involving both perceptions induced by inadequate stimuli (pressure on the eye, a battery on the tongue), and those induced by adequate proximal stimuli that do not correspond in the "usual" way to distal states of the world. Examples of the latter sort include mirages, corona, phantom pains, and so-called perceptual illusions. Consider for instance an example of great historical importance, the Purkinje effect: the inversion in relative saturation between red and green regions of the spectrum in low light conditions, as when the same roses that appear a vivid, deep red at noon appear relatively muddy and dim against richly green leaves at dusk. The stimulus here, an illuminated rose, is adequate for color experience, yet the phenomenon is "subjective" in the sense that the appearance of the rose changes while its objective properties remain stable. Psychophysics investigates phenomena such as this by isolating aspects of sensation for comparison—for instance, one might quantify the effect by asking subjects to match the red of the rose under each lighting condition to standardized reference stimuli, such as Munsell color chips.

J. J. Gibson (1960; 1966; 1986) questioned the significance of experiments such as this, arguing that psychologists should focus on perception as it occurs in realistic contexts. Traditional psychophysics ignores the richness of the real world and the cues it provides, measuring instead isolated sensory qualities, induced by artificial stimuli and contrived experimental setups. Müller's subjective phenomena may only be identified and described through such isolation and artifice—the hue of the afterimage only appears of a kind with hues of ordinary surfaces when we unnaturally attend to circumscribed regions of the visual field, ignoring its structured, holistic character. This focus on artificial, proximal, unusual, or inadequate stimuli provides evidence for physiology, not psychology. Psychology proper "should try to discover what an organism is responding *to*, not what excites all the little receptors" (Gibson 1960, 700). This means focussing on organisms as wholes and the kinds of stimuli to which they typically respond, namely "stimulation that comes in a structured array and that changes over time" (Gibson 1986, 56). Unlike the isolated stimuli of traditional psychophysics, the rich, dynamic patterns of ambient information in a real environment uniquely "specify" their source in a manner that organisms may "pickup" (56–7). Epistemically, this ambient information directly conveys facts about distal objects to perceptual experience, escaping the apparent skeptical trap inherent in subjective phenomena.

In order to confront the full force of Gibson's critique, it is necessary to acknowledge just how radical it is: Gibson's claim is not merely that traditional psychophysics has focused on the wrong parts of experience or the environment, but rather that psychology needs to completely reconceptualize both experience and environment. As such, Gibson's methodological claims are entangled with metaphysical ones—one cannot meaningfully study perceptual experience by studying isolated sensory qualities because experience is not *composed* of such qualities, but is properly conceived as an *irreducible dynamic whole* (Gibson 1966, 2–5, 56). This metaphysical picture has direct epistemic implications: if perceptual experience is not composed of simple sensations, then "sense impressions are not the 'raw data' of perception," nor its "given" (48).

Nevertheless, I want to set Gibson's metaphysical position and its epistemic implications aside until Section 3.2, and here focus solely on the question of evidence. Müller's claim concerns which phenomena are relevant to the science of perception, and it should stand or fall independent of any particular theoretical description or metaphysical analysis of those phenomena. While Gibson may choose to describe phenomena such as afterimages or the Purkinje effect in very different terms than Müller, he does not deny that they occur. Rather, he denies that such phenomena reveal anything pertinent to the understanding of perception proper, namely our ability to extract invariants from ambient information in the environment (Gibson 1986, 238–250). This is because phenomena such as corona and afterimages "do not seriously interfere with the getting of information ... They only distract the attention from the registering of objective facts" (Gibson 1966, 306). Do these considerations undermine the claim that subjective phenomena are of primary *evidential* importance for a science of perception?

The mainstream view attributes importance to subjective phenomena in part for the very reason Gibson rejects it, namely the role they play in revealing the details of underlying mechanism. For instance, Helmholtz stresses that perceptual "illusions" are scientifically important precisely because, by forcing a breakdown in the veridicality of sensory experience, they probe the process by which veridicality is typically achieved. Consequently, such "illusions" should not be understood as indicative of any error in the mechanism of perception, which proceeds as always; rather, they illuminate this mechanism truly:

> [W]hen the modes of stimulation of the organs of sense are unusual, incorrect ideas of objects are apt to be formed; which used to be described, therefore, as *illusions of the senses*. Obviously, in these cases there is nothing wrong with the activity of the organ of sense and its corresponding nervous mechanism which produces the illusion. Both of them have to act according to the laws that govern their activity once for all. It is rather simply an illusion in the judgment of the material presented to the senses, resulting in a false idea of it. (1962 [1910], 4)

While "illusory" phenomena may not typically interfere with veridical perception of environmental features, they may still reveal how typical information pickup occurs—insofar as typical information pickup is the target of a theory of perception proper, then even Gibson should be interested in subjective phenomena and treat them as a primary source of evidence, a point made forcefully by Shepard (1981):

> To say that there is sufficient information in the proximal stimulus and even to point to some of the higher-order variables in which the requisite information resides is not to describe the mechanism that extracts that information and uses it to control appropriate behavior or additional cognitive processing. That the perceptual system is governed by internalized rules becomes evident under those "impoverished" circumstances in which the proximal stimulation fails to contain sufficient information for the unique determination of the three-dimensional scene ... The perceptual system is not simply transparent to the incident stimulation. The

> inner machinery that underlies its selectivity in the face of greatly reduced external information does not simply go away when the conditions of observation improve. ... Under normal circumstances, our perceptual system ... gives rise to the illusion of transparency ...; but it is only an illusion. (Shepard 1981, 285–6)

Now, if this line of response to Gibson concerned only the investigation of subpersonal aspects of perception, then it would fail—Gibson is happy to acknowledge the value of traditional psychophysics for uncovering facts about the neurophysiological mechanisms of sensation. But the "laws" of neural mechanism which Helmholtz and Shepard invoke are not only subpersonal, they are reflected also in law-like constraints on the phenomenology of perception: what it is like to have a particular experience, and consequently also the epistemic implications of such experiences. It is these law-like patterns in phenomenal experience that psychophysics discovers, and it is precisely their law-like character that allows them to serve as evidence for underlying sensory mechanisms. Insofar as subjective phenomena probe in the first instance the personal-level features of perceptual experience, though, it seems they must be acknowledged as a significant source of evidence for theories of perception proper.[5]

To see this, consider for instance the case of afterimages. Gibson is correct that afterimages rarely interfere with our effective perception of or navigation through natural environments; likewise, they have been an important source of evidence on the physiology of color vision. But afterimages are also an important source of evidence for theories of the phenomenology of color experience. In the late 19th century, careful introspective analysis of afterimages inspired Hering's opponent model of the space of possible color sensations. The oppositions between blue and yellow, and green and red, that motivate opponent color theory could only be derived from a careful examination of "subjective" sensations, since these oppositions simply do not exist in the external correlates of color. Yet opponent color theory is manifestly a theory about what the experience of colors is like, and which combinations of colors are phenomenologically possible—it predicts and, if correct, explains why greenish red is not a possible color experience, yet yellowish red is. Likewise, the Purkinje effect provides evidence about low-light receptors, but it also describes a law-like regularity in our visual experience of a dynamic environment. Similar considerations apply to all of Müller's subjective phenomena.

So, subjective phenomena constitute a source of evidence on phenomenal regularities, and thus on perception proper. By their nature, as phenomena occurring when perceptions differ from the "usual" case, or varying with observer's perspective as stimulus remains constant, these experiences do not reveal the intrinsic qualities of their physical causes; consequently, to accept them as evidence is to acknowledge the empirical basis for the Doctrine's skeptical conclusion. It is worth stressing, however, that this is meant as an inclusive point, not an exclusive one. I reject Gibson's negative argument, against the relevance of subjective phenomena to perceptual science proper, but I do not mean to undermine his positive project, to study perceptual experience in the context of rich, dynamical cues. Notice that the paradigmatic examples we've considered to motivate Müller's position involve color, a quality on

[5]This does not address Gibson's statistical point: that subjective phenomena are rarely attended to, or rarely interfere with veridical perception. I take it that these statistical considerations are not relevant to the evidential question addressed here—a comprehensive science should explain even very rare phenomena (although I think the rarity of subjective phenomena has been overstated). Rather, I think they are intended to support Gibson's metaphysical and epistemological views. Nevertheless, when addressing those views below, I will focus on Gibson's idea that we directly perceive structured aspects of the environment, rather than his statistical claims; this is because I think structuralist arguments support a much stronger epistemological position than mere statistical regularity—see Section 3.3, below, and Part I, Section 3.2, for further discussion.

which Gibson had little to say. In contrast, Gibson's view is motivated largely from considering spatial perception. In fact, for Müller, as for Gibson, there are important epistemic differences between color and spatial perception, differences on which they largely agree—a point that will become clear as we examine the philosophical implications of these empirical results.

3 Naturalistic Epistemology of Perception

So, by the lights of the science of perception, the qualities we perceive are not determined by, and so do not directly reveal, the properties of their external causes. May we nevertheless attain some knowledge of the world, or does this "skeptical conclusion" open the floodgates to global skepticism? Both Müller and Helmholtz argue that the Doctrine is compatible with a form of realism, namely *epistemic structural realism*—the view that we may know relations that obtain between properties and objects in the world, while remaining ignorant of their intrinsic natures. Contemporary philosophy of perception offers a more fertile field for realist strategies than the landscape with which Müller and Helmholtz were familiar; nevertheless, this section argues that, for a broad class of naturalistic attitudes, structuralism still poses the most promising route to perceptual realism.

Naturalists hold that philosophy should cohere somehow with the scientific worldview. More specific naturalisms vary widely, from those that eschew scientific detail, focusing instead on intuitively non-supernatural metaphysics, to those that defer completely to the sciences, endeavoring to read the solutions to philosophical problems directly off current theory. For the present purposes, I will restrict attention to naturalisms that take themselves beholden to the details of current science, distinguishing two broad attitudes, which I'll call weak and strong naturalism. Weak naturalism demands merely that philosophical theory be consistent with scientific ontology, while strong naturalism demands further that the ontology of philosophy be identical to that of science.

To see why the distinction matters, consider, for instance, the psychophysical result that colors due to inadequate stimuli (e.g. afterimages) and those due to adequate stimuli (illuminated surfaces) are of the same phenomenal type. If one is a strong naturalist, then one is forced to acknowledge that there is no empirically motivated difference in kind between these experiences, and consequently, one can make no appeal to such a difference in solving epistemological problems of color perception. Conversely, the weak naturalist may feel comfortable stipulating they are of different ontic, *a fortiori* epistemic, types—such a distinction could not be defended within perceptual science, but stipulating it is consistent with that science, in the sense that it adds no new objects to the world, but merely re-categorizes those already on offer. Weak naturalists are thus at liberty to draw new distinctions, or re-prioritize the objects and events of perceptual science, in ways that strong naturalists are forbidden.

For the strong naturalist, the defense of realism has turned largely on questions about the nature of the mechanism leading from sensory stimulation to conscious experience. One issue here is whether this mechanism performs an inference. If so, then it would seem that our perceptual knowledge of the world may only be as justified as the conclusions of any instance of that inference type—a worrisome result should perceptual experience be generated by an inductive or abductive inference. Second, following Gibson, some philosophers have put much weight on the role of action and active engagement with the world in determining perceptual experience; the intuition is that perception-action loops serve to distinguish adequate from inadequate sensations, as only the adequate ones successfully guide action. As usual, Helmholtz is at the center of both these issues; surveying the state of the art reveals few alternatives for the strong naturalist to Helmholtz-style structuralism.

The section concludes by returning to the position of the weak naturalist. While she is at liberty to ground perceptual knowledge in simple sensory qualities, this move leaves perceptual knowledge far more coarse-grained than the richness of our experience. Thus, even the weak naturalist should find structural realism an appealing response to the Doctrine's skeptical challenge.

3.1 The Question of Inference

If the skeptical conclusion of the Doctrine is correct, and basic sensations do not directly reveal their causes, how do we nevertheless form a stable and effective perceptual picture of the world? Helmholtz argued that perception results from an inductive, or analogical, inference: from our past experience of associations between primitive sensations, we infer the most likely distal causes. Helmholtz took these inferences to be analogous to those performed in science, and thus our perceptual experiences to be "conclusions," every bit as defeasible as the conclusions of science (Helmholtz 1962 [1910], Section 26). If this view is correct, and our perceptual experience is a defeasible hypothesis constructed through association, analogy, or induction, then it appears that perceptual "knowledge" of the world may be sparse at best, and impossible at worst.

The next subsection will elaborate on Helmholtz's own solution to this worry. Here, I want to disentangle three issues that have been conflated in the debate over perceptual inference: (i) the empirical question of what mechanism leads from peripheral sensory stimulation to full-blown perceptual experience; (ii) the methodological question of whether it is constructive to emphasize an analogy between the unconscious perceptual processes that result in experience and conscious inference of the kind we see in scientific reasoning; and (iii) the logical question of the evidentiary relationship between the input and output of a perceptual process. I'll tackle these issues in reverse order.

My own view is that Helmholtz should be read as making a claim about the logical structure of perception. Any input–ouput process for which one can assign a semantic interpretation to both input and output may be treated as a form of argument, with the input serving as premises and the output as conclusion. Argument-types may be categorized through the schematic relationship that obtains between premises and conclusion (Peirce 1955 [1883]). For instance, an inductive argument takes as input the constant conjunction between two properties, or an object and a property, and delivers a rule about their relationship; in contrast, a (simple) deductive argument takes as premises a rule and antecedent to that rule, delivering as conclusion its consequent. The logical structure of a process is the schematic argument profile instantiated by its inputs and outputs.[6]

If one accepts the Doctrine's skeptical conclusion, then the input to a perceptual process is information about the state of sensory nerves. If the output of this process is a rich experience of a distal world, then at the very least, we know the logical structure of that process is ampliative, and this in turn tells us something about the degree of evidential support that obtains between the stimulus that instigates perception and the culminating experience of it. If one takes this evidential relation to be relevant for the epistemology of perception, then it follows from its ampliative character that our experiences of the

[6] Helmholtz identifies a "new sense impression" as the "minor premiss" and a learned association between sensations as the "major premiss" of a perceptual inference, which itself exemplifies "an elementary process lying at the foundation of everything properly termed thought" (1977 [1878], 132; cf. 1962 [1910], 24–7).

world have the same, defeasible epistemic status as the conclusions of an ampliative argument in, say, the sciences (cf. Peirce 1955 [c.1902]). I take Helmholtz to be motivated by considerations of this form when he argues that perception is analogous to scientific reasoning, and that this conclusion is relevant for the empistemology of perception.

This logical question is distinct from the physiological one: what mechanism generates perceptual experience from sensory input? If this mechanism may be interpreted as the manipulation of representations, i.e. bearers of content, then we may ask whether it follows steps that mirror the structure of any particular type of argument. This argument may differ in logical structure from that we ascribed merely by looking at the inputs and outputs. For instance, the inputs to a process may include enough information to derive the output deductively, but the internal mechanism may fail to utilize that information, and instead derive the output through an inductive procedure. Conversely, a problem that appeared to have the logical structure of an induction may be solved through a deductive mechanism, if that mechanism employs a hidden, but independently justified, premise. For instance, it may appear that perception of a red apple as ripe and comestible must be the result of an induction over past experiences of redness and their association with edibility; however, if the mechanism leading from sensed redness to perceived edibility draws on an evolutionarily instilled rule, that bright redness implies edibility, for instance, then it may derive the output deductively.

Absent a theory of perceptual mechanisms, the strong naturalist might take the logical structure of perception to serve as a guide to its epistemology. I don't think this epistemic maneuver is undermined in any serious way by early worries about the inference view, for instance that of Köhler (1971 [1913]) discussed above (Section 2.1). In his attack on the constancy hypothesis, Köhler attacked the appeal not only to unnoticed sensations, but also to unconscious inferences. But this is a methodological criticism—Helmholtz's inference view is not permissible as an empirical theory of perception, since it posits unconscious states that may be redescribed or stubbornly reasserted in response to any putative criticism, rendering the theory unfalsifiable by consciously accessible means. This is essentially a point about the relationship between evidence and theory in psychophysics, not about physiology or epistemology. Rather, the epistemological point rests only on an ability to ascribe content to the input to perceptual processes, and this may be done by appeal to the physiology of perception, independent of considerations about what is noticed or conscious from a phenomenological or psychophysical perspective.

More recent critics of the inference view have focused on disanalogies between perceptual processes and prototypical inferences. Some of these disanalogies undercut the logical claim, others the mechanistic claim, and some both. For instance, if one takes typical inferences to be entirely conscious, then the unconscious nature of putative perceptual inference is a point of disanalogy. This disanalogy might imply that thinking of perception as inference will not be helpful for discovering its mechanism—again, a methodological point. Conversely, the disanalogy may pose problems for the logical claim, if one takes it that unconscious mental states may not be assigned propositional content. Finally, if one holds that only conscious states are relevant to epistemology, then the logical structure of perception will be deemed irrelevant for questions of knowledge. Kaplan (2002) for instance, moves from the last of these considerations to the first (cf. Hamlyn 1977); Hatfield (2002) stresses both the first and the second; while Rock (1983) defends the inference view against arguments from disanalogy.

While the methodological side of this question is important, and not constrained in any interesting way by the Doctrine, the most important issues about perceptual inference for today's strong naturalist concern the candidate mechanisms for perceptual processing. For, unlike the time of Helmholtz, there are a number of concrete, well-specified candidate mechanisms available, and thus one may analyze their epistemic implications directly rather than relying on mere logical analysis of the problem of perception. Whether or not one accepts the principled worries that perceptual processes are disanalogous to prototypical inference, a number of the proposed mechanisms *appear* to be explicitly inferential. This is because they employ the mathematics of Bayesianism, and this mathematics is typically discussed, and indeed was first proposed, as a form of inference.[7] Confronting the empirical success of these models, the strong naturalist would be unwilling to accept the attitude of Kaplan (2002), who simply denies that Bayesian models are appropriate for perception *a priori*. Rather the more appropriate naturalistic question is: *given* that perceptual processes are best modeled by Bayesian mathematics, what does that tell us about the epistemology of perception?

A nice example of this kind of debate is the recent exchange between Andy Clark (2017a, 2017b) and Jakob Hohwy (2016, 2017). Clark and Hohwy are both proponents of the predictive processing (PP) framework in cognitive science. PP posits the nervous system is structured in a hierarchy of Bayesian models, each predicting the behavior of the one below. A Bayesian model begins with a prior probability distribution over a set of elements, typically described as "events" or "worlds"; then, given some input set of events (or partial reassignment of probabilities, Jeffrey 1965) it updates the probability distribution to a posterior set of values by Bayes' rule. Bayesian models such as this are commonly used to analyze scientific inference (Shimony 1970; Howson and Urbach 2006); furthermore, introductions to PP routinely cite Helmholtz's inferential view as a precursor, and present the view as continuing or reviving his insights into the inferential nature of perception.

Both Hohwy and Clark take perception to be inferential in some Helmholtzian way, yet draw very different epistemological conclusions. Hohwy defends the reactionary view that the inferential character of perception implies a veil of uncertainty separates our experience from the world, perception is indirect, and thus we should embrace some variety of skepticism. In contrast, Clark takes the inferential character of the PP model to be counterbalanced by considerations of embodiment and active exploration, opening the door to a direct realist epistemology of perception—this response bears more resemblance to Helmholtz's own than is typically recognized, and I elaborate on it in the following subsection. At least two further responses are possible, however.

One response is to apply the worries of Hatfield and Hamlyn directly to the mechanism of PP, arguing that low-level Bayesian processes are not in fact inferential, since their status as unconscious, or subpersonal, blocks the attribution of content, and content attributions are required for a process to be identified as inferential. I think there is something that this criticism gets right: namely, we should distinguish the mathematics of Bayesianism from the interpretation of that mathematics. The fact that Bayesian mathematics provides an empirically adequate model for some neural mechanism does not thereby imply that the interpretation of that mathematics as involving inferences over sets of worlds and their respective degrees of possibility follows as well (cf. Bruineberg, Kiverstein, and Rietveld 2016). Consider, for instance, the synchronization of weakly coupled oscillators, a mathematical model that applies to a variety of phenomena, such as the ticking of clocks attached to the same wall, or the pulsing light of fireflies in the same bush; no conclusions whatsoever may be drawn about functional or semantic similarities across these divers oscillations from the mere fact that they satisfy the same

[7] For a relatively early survey and exposition, see Knill and Richards 1996.

model—mathematic structure simpliciter determines neither ontology nor epistemology. Ultimately, the question of how to interpret the mathematics of PP must be resolved within that research program, and while empirically-engaged philosophers are part of this discussion, the epistemic implications can only be assessed after that debate is resolved.

A final, more pertinent response is exemplified by Drayson (2017), who argues that the physiological / psychological question of whether perception exhibits an inferential structure may be completely detached from epistemic considerations. I take this move to exemplify weak naturalism, and return to it in Section 3.3.

3.2 The Answer from Action

While interpretations of Helmholtz's epistemology range from idealism (Heidelberger 1995), through Friedman's (1997) transcendental empiricism, to realism (McDonald 2002), I read him as an epistemic structural realist (as have others, e.g. Moulines 1981; Hatfield 1990, 2018). Part I argued that Müller's own response to the Doctrine was a form of structural realism, but Müller and Helmholtz differ substantively in the motivations for their structuralism. Müller's structuralism was motivated largely by his Herbartian theory of the mechanism of concept formation (Part I, Section 2). While Helmholtz was also influenced by Herbart (Lenoir 2006; Isaac 2013), he was more reticent than Müller in his assumptions about cognitive mechanisms. Rather, I take Helmholtz's structural realism to follow from the constitutive role he saw for action in determining perceptual content (a role nascent in Müller, see Part I, Section 3.2). By including active exploration as part of the mechanism of perception, Helmholtz is able to mitigate the epistemic worries introduced by the observation that the logical structure of perception is inferential, and restore a form of perceptual realism. There are close analogs here to the view of the archetypal direct realist, Gibson, as well as to those of philosophers who have followed in his stead (e.g. Noë 2004; Chemero 2009; and Clark's 2016 embodied PP). The most convincing interpretation of their action-centric arguments does not imply stable access to simple properties in the world, but rather epistemically robust ("direct") access only to those structural relationships that hold *between* such properties—an epistemic position in agreement with Helmholtz on the question of *what can be known*, and in that sense consistent with the Doctrine's skeptical conclusion.

A classic worry in perceptual science has been the underdetermination problem: the proximal information available to sensory surfaces at any moment underdetermines its distal causes. For instance, a square-shaped visual sensation underdetermines the shape of the object that cast it, since an infinite number of differently shaped and sized quadrilaterals may all cast the same square-shaped projection on the retina if suitably arranged. Likewise, a sound heard at particular loudness and pitch underdetermines its cause, which may be distant and very loud, or close and relatively soft. If one acknowledges underdetermination, it appears to drive one to inferentialism: since our immediate experience does not provide definitive evidence for the properties of the stimulus, we may at best infer them.

Gibson (1986) rejected the claim that the information available to sensory systems underdetermines distal causes. He argued that the underdetermination worry rests on a mischaracterization of the stimulus. In general, our sensory systems do not receive static information that underdetermines distal causes; rather, we receive dynamic patterns of information that "uniquely specify" distal causes in the environment (74). For instance, if we move our head or body, then we disambiguate the many possible quadrilaterals that might cast a square projection on the retina; if we turn our head, we disambiguate, through subtle changes in reverberatory properties, near from far sound sources. In general, once we recognize that perceivers move and actively explore their environment, then we see that the information available to them is dynamic and structured, changing in systematic ways over time.[8] If Gibson is right, and these structured, temporally extended patterns of information in the environment uniquely specify their distal causes, then there is no principled barrier to our perceptual systems providing us with direct access to those causes in the world (47–92).

Although Gibson explicitly presents this view as contrasting with that of Helmholtz, I think a closer comparison reveals that, while their metaphysics of perception may differ greatly, the epistemological implications of their positions are closely aligned. Helmholtz held a "sign" (*Zeichen*) theory of perception, on which our experiences come in an innately determined vocabulary of arbitrary symbols—colors for vision, pitches for audition, pressures for touch, etc. (Helmholtz 1977 [1878]; Hatfield 1990, 208–11). This minimal innateness hypothesis builds naturally on the Doctrine's conclusion: if basic sensory qualities are determined in the first instance by the activity of our nerves (rather than their distal causes), it makes sense that these qualities be somehow innately constrained. Nevertheless, arbitrary symbols are not yet bearers of content, they are merely *potential* bearers of content. These symbols come to serve as signs for external properties through experience, but they must be understood as mere signs, rather than "images" (*Abbilder*), since they bear no similarity to the properties they indicate (Helmholtz 1977 [1878], 121–2).

What additional ingredients are needed to imbue these innate symbols with content? Helmholtz's epistemology requires two. The first is the *causal law*, an assumption of regularity in the relationship between sensory signs and their distal causes, i.e. a kind of "law of lawfulness" (Hatfield 1990, 211). The causal law allows us to infer distinctions and invariants in the properties of the world from changes and stabilities in experience, and thereby bootstrap our way to an understanding of physical laws. It thus serves the role of a transcendental principle, one without which coherent experience itself would be impossible, and upon which science is grounded. Debates over exactly where Helmholtz should be positioned on the spectrum from realism to idealism turn significantly on questions about his evolving attitude toward this causal law; in particular, whether or not it implies realism about causality *per se*, and whether it may be justified transcendentally or must be accepted without justification.[9]

I will return to the causal law in Section 4; here, I want to grant the causal law and explore the best case scenario for an epistemology of perception consistent with the Doctrine. For this we need to turn attention to the second ingredient Helmholtz requires to imbue signs with content: *action*. For, if the casual law allows us to infer features of the world from changes in our sensory signs, it can only do so in conjunction with a process for generating such changes or invariants. Here, Helmholtz takes volitional

[8]Movement is not the only factor contributing to the disambiguation of stimuli: for instance bilateral disparity (not just between eyes, but also ears, nostrils, etc.) is a feature of sensory systems that typically operates to greatly reduce the potential for ambiguity in the proximal stimulus. Nevertheless, binocular vision by itself does not resolve the visual underdetermination problem, as the identical appearance of convex busts lit from above and concave masks lit from below demonstrates. In general, from a mathematical standpoint, static sensations will never uniquely specify their distal cause, a result that Gibson held to be irrelevant for understanding perception in an ecological context. I set this issue aside here in order to focus on the positive role of action in veridical perception. For a concise exchange in this debate, see e.g. the dispute over the relevance of the Ames Room illusion to Gibson's claims (Gehringer and Engel 1986; Runeson 1988).

[9]For some subtle articulations of various positions within this debate, see Friedman (1997), Patton (2009), and Hatfield (2011). My own view is that Helmholtz's texts sufficiently underdetermine his exact position that a variety of readings are possible. However, the point of the discussion here is not to defend any particular, detailed interpretation of Helmholtz, but rather, taking inspiration from the rough concordance between his action–structure view and Gibson's, to motivate structuralism as the most promising route to realism compatible with the Doctrine.

action[10] to serve as the critical mechanism for producing the patterns of sensory signs that provide access to the external world. Voluntary movements allow, in the first instance, a differentiation between subject and object by revealing a distinction between sensations that change systematically with willed motion and those that do not.[11] The more specific problem, of determining the distal cause of some particular sensation, is likewise resolved through movement, for we gain knowledge about distal objects by actively varying our perspective upon them (Helmholtz 1962 [1910], 31–2; Helmholtz 1977 [1878], 125). While the "certainty" so obtained is tempered by the inferential structure of the logic of perception, and thus of a piece with scientific (un)certainty, it nevertheless constitutes a robust form of knowledge as it is grounded in "experimentation":

> The same great importance which experiment has for the certainty of our scientific convictions it has also for the unconscious inductions of the perceptions of the senses. It is only by voluntarily bringing our organs of sense in various relations to the objects that we learn to be sure as to our judgments of the causes of our sensations. (Helmholtz 1962 [1910], 30–1)

> Spontaneously and by our own power, we vary some of the conditions under which the object has been perceived. We know that the changes thus produced in the way that objects look depend solely on the movements we have executed. Thus we obtain a different series of apperceptions of the same object, by which we can be convinced with experimental certainty that they are simply apperceptions, and that it is the common cause of them all. (31)

The causal law is needed here to posit the object in the first instance (that there is some cause to the systematicity in our experience), but having granted this, the invariant pattern in our experiences itself constitutes what we can know about this object, with *experimental certainty*.

In such passages, Helmholtz appears to invoke exactly the same considerations as Gibson, yet to derive a very different conclusion. Recognizing the power of action to disambiguate stimuli, Gibson concluded that perception was direct and non-inferential; acknowledging this same power, Helmholtz re-affirms the indirect and inferential character of perception. This apparent contradiction is resolved once we recognize the profound qualitative difference between classic examples of underdetermination, such as underdetermination of shape or location, and the underdetermination posed by the skeptical conclusion of the Doctrine. For the skeptical conclusion concerns the most geometrically primitive, basic, or simple qualities of experience: colors, pitches, smells, etc. Yet shape and location are neither primitive nor basic in this sense: visual shapes are composed of complexes of colors, arranged systematically. Likewise, locations are not basic, but relative positions within a rich, extended spatial array. Helmholtz asserts that knowledge of these rich *structural* properties is possible, while denying any access to simple or basic properties in the world. This structuralism emerges in his careful exposition of spatial perception, whereby "sensation *aggregates*" (*Empfindungsaggregat*) are the evidential basis for "spatial *relationships*" (*Raumbeziehung*), such as being "side by side" (*Nebeneinander*); in general, it is "sequences" or "orderings" (*Reihenfolge*) of sensations that bear knowledge—*not* sensations themselves, which alone are mere "signs," devoid of distal content (Helmholtz 1977 [1878], 125–7; cf. Helmholtz 1962 [1910], 22, 24).

[10] The critical role for volitional action in Helmholtz has been extensively elaborated and defended in recent work by De Kock (2014a, 2014b, 2018), who has provided inspiration for the discussion here. De Kock has emphasized this feature of Helmholtz as part of a broader project exploring the extent to which Helmholtz was inspired by Fichte, an issue on which I do not wish to commit myself; for an alternative view, see Hatfield (2018).

[11] Shades of this view may be found in Müller, who explicitly argues that the movements that bring about these distinctions are first initiated within the womb (2:268/1080).

Returning now to Gibson, does he pretend to offer more than this—does his argument from active exploration to direct epistemic access subsume the geometrically simple or basic properties of the world? I think the answer is *no*—Gibson's arguments at best recover direct access to the very same structural properties that Helmholtz believes we may access with experimental certainty. The disagreement between the two does not concern which aspects of the world we may know, but rather the nature of the justification for that knowledge. Gibson endorses a radically non-reductionist metaphysics of perception that allows him to assert perception of structure does not depend on prior sensation of simple properties, and thus may be non-inferential.

That Gibson, like Helmholtz, takes perceptual knowledge to concern structural aspects of the world is revealed in his considered notion of environmental information; Gibson is explicit that the information relevant to perception is not the Shannon variety, but rather "information considered as *structure*" (1966, 245, cf. 208). Consequently, when describing the perception of distal properties, he invariably employs structural or relational terminology: "A surface is seen when the array has structure, that is differences in different directions" (1986, 151). Likewise, size perception occurs when "certain invariant ratios" (relations of relative length, etc.) are "picked up" (160), and perception of extension into the distance relies on "gradients of density" (163), i.e. spatially distributed trajectories of change in appearance. For prototypical simple qualities, such as color, Gibson does not defend direct access to them considered in isolation—such isolate colors are mere "useless dimensions of sensitivity" (1966, 183). However, structural relationships between colors do have epistemic import:

> [T]rue relative colors of the adjacent surfaces emerge as the lighting changes ... From an ecological point of view, the color of a surface is relative to the colors of adjacent surfaces: it is not an absolute color. Its reflectance ratio is specified only in relation to other reflectance ratios of the layout. (1986, 89, 91)

Insofar as colors convey information about the chemical properties of surfaces, this again is only done in a structural way, through changes or relations between colors rather than absolute color values, as when "greening" indicates "increase in chlorophyll" (98). This point has been lost on disciples such as Noë (2004), who mistakenly attributes to Gibson the view that "ripeness" may be perceived through color (124), rather than (as I read him) that *change in the degree* of ripeness, a structural rather than simple quality, may be perceived through a *change* in color.

For Gibson, this structural knowledge is not obtained inferentially; rather, perceptual mechanisms directly access invariant structural features of the environment through "information pickup" or "resonance" (1966, Ch. 13; 1986, Ch. 14). In endorsing this view, Gibson rejects the traditional idea that perceptual experience is composed of, derived from, or based on simple, punctate parts in either space or time. Spatial experience is not composed of point color sensations (53–7), temporal experience is not composed of "momentary patterns" (254). Composition here implies in the first instance a claim about perceptual mechanisms: contra received lore, perceptual experience is not the result of a piecemeal process that begins with surface receptor firing, it occurs holistically as part of a fluid dynamic interaction with the environment.[12] A stronger reading takes Gibson to defend a metaphysical thesis as well: the

[12] Gibson himself did not propose a specific mechanism for perception (hence the critical remarks of Shepard, above), and there is yet no consensus on a single, viable candidate amongst ecological psychologists. Nevertheless, progress been made: Runeson (1977), for instance, gives some suggestive remarks and a proof of concept for the kind of "smart mechanisms" Gibson needs; following in his footsteps van de Grind has developed "smart," or "non-computational," models of sensori-

holistic, structural features of experience are ontologically primary, while fragmentary, circumscribed features are derivative, or supervene on them—by slight abuse of terminology from philosophy of science, we might call this an *ontic structural realism*.[13] This reading makes sense of some of Gibson's more cryptic claims, for instance, that scanned information "*contains* the scene ... it does not have to be converted into one" (1966, 262), that "the perception of the layout, the shadowing, and the reflectance of surfaces are mutually dependent" (215), or that perception is "sensationless" (2) and thus "[w]e do not perceive stimuli" (1986, 55). Nevertheless, this strong metaphysical reading of Gibson does not contradict the skeptical conclusion—it does not assert that our experience of simple qualities reveals the intrinsic nature of simple properties in the world—rather, it rejects the claim that we typically perceive simple qualities at all, or that they hold any epistemic significance.

So, adding action to the mechanisms of perception allows one to achieve structural knowledge of the world. This epistemic structural realism is agreed upon by both the paradigmatic (pro-Doctrine) inferentialist Helmholtz and the paradigmatic (anti-Doctrine) direct realist Gibson. Where they disagree is in the justification for this structural knowledge: for Helmholtz it is derived inferentially from simple sensations, and at best on par with experimental certainty; for Gibson, structure is picked up directly, and not composed of simple sensations, consequently permiting an even more robust realism. Whether she endorses an inferentialist or a direct resonance mechanism, then, the strong naturalist should respond to the skeptical conclusion by adopting a structuralist epistemology.

3.3 A Dilemma for Naturalistic Foundationalism

While the epistemology of the strong naturalist is heavily constrained by the details of perceptual science, that of the weak naturalist is more autonomous. In particular, the weak naturalist need not take the psychology of perception to determine in any way which states are epistemically basic. From this perspective, one might hold that the mechanism of perception is inferential, yet the epistemology of perception is not; for instance, if only consciously accessible states and processes are taken to serve an epistemic role. Proponents of this approach typically take geometrically basic perceptual qualities, such as colors and pitches, to be epistemically basic. Yet this strategy must accept widespread error in the ground for perceptual knowledge, a dismaying outcome greatly mitigated by taking structural relations to be epistemically basic, as these enjoy much broader domains of invariance. Thus, even the weak naturalist should adopt some form of epistemic structural realism.[14]

The idea that the epistemology of perception may be autonomous from the science or metaphysics of perception is surveyed by Lyons, who presents it as a form of "modest foundationalism." The idea is that (some) perceptual beliefs may be taken as epistemically basic, i.e. requiring no justification. On this view, the unconscious mechanisms that produce perceptual states are irrelevant to the epistemic status of these states, whether or not these mechanisms are inferential, precisely because they are unconscious. It is only conscious beliefs that participate in processes of reasoning and justification, perceptual beliefs are not derived by any such processes from other beliefs, but revealed directly in experience, so they may be

motor activity (1990); and evidence for neurons that detect holistic patterns of the sort these models need (e.g. of "optic flow") has been found by Duffy and Wurtz (1991).

[13] In philosophy of science, there have been serious concerns about whether the idea that structural relations are ontologically prior to relata is coherent (Wolff 2012; McKenzie 2017)—these worries apply *mutatis mutandis* to OSR as a claim about the ontology of perception, and will need to be confronted by defenders of this strong program in ecological psychology.

[14] This section has benefitted from discussion with Zoe Drayson.

taken as epistemically fundamental, resulting in an "epistemological direct realism" (2017, Section 3.4).

Drayson (2017) helpfully illustrates this strategy with her intervention on the debate between Clark and Hohwy concerning the epistemological implications of predictive processing. She argues that Clark and Hohwy confuse three distinct types of direct/indirect dichotomy in the study of perception: psychological, metaphysical, and epistemological. While the mechanism PP proposes for perception may indeed be inferential, and thus imply indirect access to the world *in the psychological sense*, this result nevertheless has no obligatory implications for either metaphysical or epistemological questions of directness. In particular, acknowledging that the mechanism of PP is inferential does not thereby imply (as Hohwy claims) an "evidentiary boundary" between experience and the world, since without further argument there is no reason to suppose that this mechanism "imposes evidential requirements in the first place" (17). And it is only if the subpersonal mechanisms of perception do impose such requirements, i.e. participate in or constrain the justification of knowledge claims, that the psychological (in)directness of perception would have implications for its epistemological directness.

This, then, is a potential weak naturalist response to the Doctrine's skeptical conclusion: perceptual properties provide knowledge of the world because they are epistemically basic, i.e. the apparent access we have to properties in the world through experience requires no further justification.[15] It may be that, as the skeptical conclusion asserts, basic experiences do not reveal anything about the intrinsic nature of their causes, but this need not bar them from grounding facts about those causes. For instance, one might hold that the intentional content of a perceptual experience is its adequate stimulus, e.g. the content of a red experience is some particular surface reflectance property, the content of a "rotten egg" smell is sulphur, etc. Then, experiences that attribute red or pungent smells to the world would be veridical if the corresponding property were present.[16] Sure, Müller may have shown that on very rare occasions the corresponding property is not present (there is no colored surface that corresponds to the sensation from pressure on the eye), but typically experiences are caused by their adequate stimuli, and thus taking simple perceptual qualities to ground beliefs about their causes is epistemically secure.

The problem with this line of argument is that the "subjective phenomena" that provide the evidential basis for perceptual science include not only sensations due to inadequate stimuli, but also sensations due to adequate stimuli that nevertheless vary while "objective" properties remain constant. Crucially, these variations are not rare, but rampant. Consider again the Purkinje effect: the inversion in relative saturation between red and green regions of the spectrum in low light conditions is literally an everyday occurrence, one that manifests itself many times a day in the modern world during our frequent passage between bright and dim conditions as we wander through our carpentered environment. Many other color phenomena, so-called perceptual "illusions," confirm the highly context-sensitive and variable nature of color experience—colors spread into nearby neutral hue areas; they vary in hue with changes in luminance or addition of white light; contrast and brightness vary with luminance; and memory affects perceived color, to describe just a few effects (see Fairchild 2005, Chapter 6, for extensive discussion). Analogous effects are found amongst the primitive sensations of every sensory modality (e.g. touch: Akins 1996; smell: Barwich 2018).

The natural response to this worry is to appeal to perceptual constancies: despite variations in the

[15]There is a complex tangle of issues here concerning the putative transparency of perceptual properties, and the relation between apparent access to the world and actual access; I set these concerns aside to focus solely on the relevance of empirical results for the naturalistic interpretation of this position, but see Lyons (2017), for further discussion.

[16]Note that the correct account of the content of simple perceptual sensations is by no means obvious; for some radical alternatives to the standard weak naturalist semantics, see Akins and Hahn (2014) on color or Mattens (2017) on touch.

stimulus reaching the retina, for instance, our assignment of colors to surfaces remains largely constant. In fact, perceptual constancies constitute a prime behavioral motivation for inferentialism (we infer stable surface properties from a color signal that varies with illuminant), and one which does not undermine modest foundationalism (since these inferences are unconscious). The problem with this line of argument is that *strict* constancy in perceptual qualities simply does not obtain—in the words of Fairchild (2005), "color constancy does not exist in humans!" (132, exclamation point in the original). Fairchild emphasizes this point because he studies color appearance, i.e. the way colors look to us, and the contextual sensitivity of color experience poses the fundamental problem for this area of research:

> When colors are closely examined, the lack of color constancy becomes extremely clear. The study of color appearance and the derivation of color appearance models are, in fact, aiming to quantify and predict the failure of color constancy. (132)

A critical point for our purposes here is that the color sensations studied in the color appearance literature are not unconscious, nor only accessible through specialized training (thus, they are not susceptible to the methodological worries of Köhler 1971 [1913]). Rather, they are normal experiences of color, accessible in untrained subjects through psychophysical methods, introspection, or careful observation. Furthermore, this failure of precise constancy is not particular to color, but a general phenomena across all modalities.[17] The worry for modest inferentialism is then this: if our perceptual beliefs about simple sensory qualities are taken to be epistemically fundamental, then our perceptual beliefs are in widespread error, since they do not correlate precisely with stable physical features in the world.

Of course, we do experience some significant degree of color constancy, and this tempered constancy is an object of scientific study: can't this apparent constancy be levied to salvage modest foundationalism about simple perceptual qualities? For instance, one might tease apart the phenomenology of colored surfaces to include both a belief about surface color and a belief about illuminant color, thereby hoping to recover constancy in each (Hilbert 2012). Corresponding moves are possible in other modalities, for instance one might attempt to save constancy of sounds with respect to sources by distinguishing auditory features correlating with the source from those correlating with the traversed medium, as when a thud in the next room conveys information about both the falling object and the intervening wall (Isaac 2018). While this strategy is coherent and may be developed in detail, it comes at a cost: veridical perceptual beliefs involve qualities far coarser than those of perceptual experience, and thus fine-grained perceptual properties must be discounted when reckoning perceptual knowledge. But once we realize this, the claim that perceptual beliefs are not derived by any consciously accessible process becomes suspect, since they no longer coincide with perceptual experience itself. This then is the epistemologist's dilemma: either she takes perceptual beliefs to be precise, but then there is no stable external correlate to sensory qualities, and so these beliefs are in widespread error; or she takes perceptual beliefs to be vague, but then perceptual knowledge is far more coarse-grained than experience itself, and the claim that it is direct or underived loses plausibility. Modest foundationalists are welcome to bite either of these bullets as they see fit, but it is worth reflecting on the possibility of a third way.

[17] Other modalities are less well studied than color, so precise models of the kind found for color appearance are not yet available. For a discussion of analogous issues in the context of olfaction, see Barwich (2018), who rejects constancy of simple smells—"There are no stable and intrinsic links between chemicals or input sources and our perceptions such as odor qualities"—in favor of structuralism: "Smells . . . are not so much about objects and stable object perception, but about changes in the chemical composition of the environment" (338).

The dilemma arises when one takes as fundamental the simple perceptual qualities at which the Doctrine's skeptical conclusion is directed. What if a modest foundationalist took as epistemically basic the structural properties of perception: locations, shapes, *relative* colors and pitches, *changes* in odor, heat, pressure, etc.? As demonstrated above, knowledge of structural properties is consistent with the Doctrine; more generally, our experience of perceptual relations may be veridical even when experience of simple qualities is not—the exact apparent shades of these red and yellow pens may vary greatly while their objective physiochemical properties remain unchanged, yet the relation of this pen being *more red* than that will stay stable across a wide array of contexts. This is not to say that structural properties are never perceived in error; constancy fails for the metric properties of space such as size and distance, for instance (Wagner 2006). Even relative sizes and distances are susceptible to distortion under extreme conditions, as when small near objects may be confused with large distant ones in a dense forest on a moonless night or whiteout conditions during a blizzard (Clark 2016, 8). Nevertheless, qualitative relational properties, the very ones we experience, not some derived coarse graining, are typically perceived with greater stability, and veridicality, than simple perceptual qualities. So, by adopting a structuralist approach, the modest foundationalist may not completely dissolve her dilemma, but she dramatically blunts the sting of both its horns.

Weak naturalists respect a very different set of theoretical constraints than strong naturalists. Insofar as they aim to avoid widespread error and ground perceptual epistemology in phenomenally accessible qualities, however, they also will best be served by adopting an epistemic structural realism.

4 The Doctrine in Philosophy of Science: *From Evidence to Exemplar*

Structuralist approaches, and structural realisms in particular, have seen a resurgence in contemporary philosophy of science (Ladyman 2016; Frigg and Votsis 2011). This movement traces its intellectual heritage to *fin de siècle* positivism and neo-Kantianism, a period heavily influenced by Helmholtz. For both Helmholtz and his teacher Müller, the epistemology of science was closely entangled with the epistemology of perception, and analogous arguments led to some form of proto-structural realism in both domains. We might ask, then, what role the Doctrine in particular played in the origins of scientific structuralism, and whether its influence may still be felt in philosophy of science today. Ironically, the very development that spurred the rise of structuralism, the formalization of non-Euclidean geometry, for which Helmholtz himself contributed the founding epistemology, itself undermined the relevance of sensory epistemology for that of philosophy of science. Although the Doctrine no longer serves an evidential role in arguments for structural realism, it nevertheless deserves renewed attention as an exemplar for the structuralist program.

Recall that Müller endorsed an intertwined, two-fold structural realism (Part I). First, he was a structural realist about sensory epistemology: all that we can know of the world through experience are structural relations, such as relative spatial relationships or relations between cause and effect. He took this view to occupy a moderate, intermediary position between (as he saw it) the skepticism of Hume and the apriorism of Kant and Aristotle (Hatfield 1990, 152–7). But Müller was also a structural realist about perceptual science, including sensory physiology: we can discover the laws that govern the behavior of nerves, such as the Bell-Magendie law or the Doctrine itself, but we cannot know the intrinsic nature of nervous activity. This was itself an instance of his more general structural realism concerning science *tout court*: just as Newton was able to discover the laws of gravity, but not its intrinsic nature or underlying cause, so also science in general is able to discover and obtain knowledge concerning laws, but not underlying natures. Just as today's structural realists have emphasized the continuity of evidence and mathematics across theory change, Müller invoked the progress of theories of electromagnetism, light, and temperature despite radical disagreement about the underlying natures of these phenomena (fluids, particles, etheric disturbances, etc.). Nerve "energies" thus have exactly the same epistemic status as thermal, gravitational, or electromagnetic energies: empirical phenomena whose intrinsic natures are unknowable, yet about which, to the extent they exhibit patterns of regularity, we may discover laws.

Like Müller, Helmholtz recognized a continuity across the epistemologies of perception and of science, and argued that in both areas the only legitimate target of knowledge is structure. Yet our epistemic access to structure is much more fragile for Helmholtz than for Müller, for Helmholtz attributed to the mind less innate power for extracting structure from the world. For Müller, the mind has the power to "abstract" structure from patterns of sensory input in a manner that adds nothing of epistemic relevance to the input. In the case of the perception of space, this power conspires with the inherent spatiality of sensory organs to provide an epistemically fundamental spatial experience in two dimensions (Part I, especially footnote 7; Hatfield 1990, 154–5); in the case of causality, it allowed Müller to reject Hume's skepticism about our ability to know causal structure, since it may be abstracted without mediation from our experience of patterns in the succession of events. Helmholtz, however, accepted no such power, leading to his insistence that neither spatiality, nor causality, could be epistemically fundamental.

In the case of causality, Helmholtz recognized that inferences from phenomena to laws required the assumption that regular variation itself constitutes evidence for underlying causal structure. Already in his 1847 treatise on the conservation of force, Helmholtz identified this inferential principle as the causal law (*Gesetze der Causalität*), namely the assumption that every change (*Veränderung*) in nature must have a sufficient cause (*zureichende Ursache*), and argued this principle constitutes the fundamental presupposition behind natural science (2–3):

> We are compelled to and justified in [*genöthigt und berechtigt*] this undertaking by the fundamental principle that every change in nature must have a sufficient cause. The proximate causes, to which we refer natural phenomena, are themselves either invariable or variable; in the latter case, the same fundamental principle compels us to seek still further for the causes of the variation, and so on, until we arrive finally at causes which operate according to invariable law and which consequently produce under the same external conditions the same effect every time. Thus the final goal of the theoretical natural sciences is to discover the ultimate invariable causes of natural phenomena. (1971 [1847], 4)

Only when we can trace perceived variation back to some invariant principle is nature comprehensible (*begreiflich*); although it is not guaranteed that such invariants may be found,

> it is clear that science, the goal of which is the comprehension of nature, must begin with the presupposition of its comprehensibility and proceed in accordance with this assumption, until, perhaps, it is forced by irrefutable facts to recognize limits beyond which it may not go. (4)

This remarkable passage mandates a close complementarity between the methods of science and their justification. On the one hand, the natural scientist proceeds by seeking invariant principles that explain, or make comprehensible, variations in the phenomena. On the other hand, it is the assumption that this procedure is possible, and that nature is susceptible to description in terms of invariant causes, that itself justifies this endeavor.

This passage also illustrates the close analog between Helmholtz's reasoning about perception and his reasoning about science. For, in the case of perception as well, it is the variations in phenomenal experience induced by our probing of the world (analogous to experimentation) that produce structural knowledge. When combined with the Doctrine's skeptical result concerning simple phenomenal qualities, this reasoning led Helmholtz to his *Zeichentheorie* of perceptual representation. It is widely held that the *Zeichentheorie* extends to the epistemology of science, in part because Helmholtz draws analogies between sensory physiology and science in general both when discussing the former (Helmholtz 1977 [1878]; 1962 [1910]) and the latter (Helmholtz 1995 [1869]), even asserting that "science is nothing but methodologically and deliberately completed and purified experience" (Helmholtz 1971 [1894], 528).[18]

Yet, logically, a general *Zeichentheorie*-type view need not follow from perceptual considerations. For, if one recognizes that science involves the construction of representations, akin to those we use in language insofar as their primitive symbols bear no intrinsic similarity to their referents, and combines this assumption with Helmholtz's characterization of the scientific method as a procedure for determining and corroborating invariant relations in the world, then one will arrive at structuralism without appealing directly to perception at all. Helmholtz himself wanders close to this line of reasoning when he stresses that science should be understood as a mode of "concept formation" (Helmholtz 1971 [1894], 520). This view is more explicitly stated by Helmholtz's student Hertz in the introduction to his *Principles of Mechanics*. Hertz's *Bild* (or "picture") theory takes both mental and scientific representation to succeed insofar as it mirrors the relational structure of its objects, i.e. "the consequents of the images in thought are always the images of the necessary consequents in nature of the things pictured" (1899, 1). The most we can aim for in science, then, is to construct an image which is "permissible" (internally consistent), "correct" (empirically adequate), and relatively "appropriate," i.e. "pictures more of the essential relations of the object" while invoking a "smaller number of superfluous or empty relations" (2). Hertz takes such a scientific image to be analogous to a "grammar," in that it systematizes some natural system in a context-sensitive way—just as the linguist and the foreign language student consult different grammars, which may be assessed for appropriateness only with regard to their respective purposes, so also different scientific images may be evaluated only with respect to contextual criteria (40; Leroux 2001). The upshot of these considerations for Hertz's epistemology of science is that, even if one is committed to the empiricist principle that "experience alone" determines "the value or worthlessness" of some scientific image, the process of image construction itself, i.e. "the formation of ideas and the development of their relations" (Hertz 1899, 135) confers *a priori* justification on structural features of scientific theory (Patton 2009; c.f. Schiemann 1998).

These early tentative steps in the history of scientific structuralism, from Müller through Helmholtz to Hertz, imply several morals. First, not all arguments for structural realism fall neatly into the bipartite

[18]A more detailed discussion of Helmholtz's epistemology would address the change in his views over time—the "realist" passage quoted above is quite early, yet later writings on perception are more circumspect concerning any ontological implications of the causal law (cf. footnote 9). Nevertheless, Helmtholtz's perspective remains resolutely structuralist throughout, and my intent is to illustrate this feature, while eliding subtle exegetical questions.

taxonomy of Psillos (2001). Psillos identifies an "upward path" and a "downward path" to structural realism: the first begins from general empiricist considerations, for instance that knowledge is grounded in perception, and strives toward a tentative realism about science in particular; the second begins from a realist commitment to the epistemic value of science, and falls back on a structuralist epistemology in response to challenges from underdetermination or incommensurability. Yet the structural realism of Müller and Helmholtz is grounded in an *analogy* between perception and science that treats neither as foundational: their structuralist account of scientific knowledge is indeed informed by their understanding of the epistemology of perception, yet their mitigated realism about perceptual knowledge is (conversely) a consequence of their commitment to the epistemic significance of results from the science of perception.

A second moral concerns the role of perceptual epistemology, and thus the Doctrine, in even the upward path toward structural realism. The views of Müller and Hertz illustrate how empiricist considerations may derive from a theory of concept formation, or even general considerations about the nature of language and symbolic representation,[19] without needing to detour through the details of perception itself. So, while the contemporary, upward path structural realist who grounds epistemology in perception will find the Doctrine a welcome ally, it may be irrelevant to those upward path structuralists whose empiricist inclinations are otherwise motivated. Unlike contemporary philosophy of perception then, which must attend to the Doctrine on pain of violating naturalism, contemporary philosophy of science, it seems, may safely ignore it.

Nevertheless, a third moral hints at a new role for sensory physiology in the contemporary dialectic. The trajectory from Müller through Hertz was shaped in part by two emerging notions that have proved critical for philosophy of science well beyond the bounds of the realism debate: *isomorphism* and *invariance* (Leroux 2001; Daston and Galison 2010, Chapter 5; cf. Suppes 2002). An isomorphism is a structure-preserving map, a mathematical relationship that characterizes sameness or similarity of structure. Hertz's description of the relationship between a scientific image and the world can be read as a demand for isomorphism: relations of necessary consequence must be preserved across the map from images to objects in nature. Helmholtz characterized the construction of such images in terms of the search for the invariants that explain apparent variation in the phenomena. A tentative moral then is this: whatever we name these invariants (laws, causes, regularities, etc.) it is their invariance itself that is the relevant feature preserved across isomorphisms. This lesson may be learned even from Müller, whose mechanism for the power of abstraction allows differences between ideas to fade leaving only what is common amongst them, i.e. the invariant features of the general concept (Part I, Section 2). This lesson applies wherever isomorphism is taken as the relevant notion for comparing parts of science, for instance the semantic view of theories (Suppe 1977), a view adopted not only by structural realists (Ladyman 1998), but also other forms of realism (Chakravartty 2001) and empiricism (van Fraassen 1980)

Invariance across isomorphism emerged as the critical concept for modern geometry, as well; a development that found its first epistemologist in Helmholtz, but which, ironically, itself spurred the shift from perception to conception as the heart of empiricist philosophy of science. Although non-Euclidean geometries had already been discovered by Gauss and Lobachevsky, it was Reimann's *Habilitation* of 1854 that introduced the formal notion of a *manifold* as the most general geometrical structure, including a

[19] Another proto-structuralist, Poincaré, illustrates this point as well, although his philosophical views developed independently of the trajectory considered here. Poincaré takes objectivity in science to turn on what can be communicated, and since only relations may be communicated, "the sole objective reality consists in the relations of things" (Poincaré 1958 [1905], 350; Brading and Crull 2017)

conceptual analysis of distance (or metric) as the superposition of magnitudes. In 1868, Helmholtz published the first of a series of investigations into the epistemological implications of this new geometrical framework, which he had discovered independently. Helmholtz points out that the principle of measurent of distance by superposition allows inhabitants of a non-Euclidean world to empirically discover the geometry they inhabit, thereby refuting Kant's claim that geometrical structure is given *a priori* in intuition (Helmholtz 1977 [1868]). What must be assumed for this analysis to proceed, however, is the rigidity of rods, or the invariance of their lengths. In 1872, Klein's Erlangen program followed this line of reasoning to its logical conclusion, individuating geometries in terms of the structures they take to be invariant, equivalently, the transformations (i.e. automorphisms, or isomorphisms of space onto itself) that leave their axioms unchanged.

These mathematical developments became fundamentally important for the epistemology of science with the discovery that physical laws remain invariant across the Lorentz transformations, a result culminating in Einstein's General Theory of Relativity, on which physical space is non-Euclidean. While Helmholtz's initial epistemology of non-Euclidean geometry was motivated in part by considerations of what was innate or not in our perception of space, the discovery that space was actually non-Euclidean motivated a crisis in philosophers' understanding of scientific concept formation, seemingly distancing it from any grounding in perceptual experience. Divergent responses to this crisis manifested themselves in the work of the two 20th century philosophers who most explicitly acknowledged an early debt to Helmholtz: Schlick and Cassirer (Ryckman 1991; cf. Gower 2000).[20] Both took the concept of isomorphism (more properly its terminological precursor *Zuordnung*, or "coordination," Ryckman 1991, 69) to capture the fundamental insight from Helmholtz's *Zeichentheorie* for analyzing the epistemological implications of the new science. Yet they differed in their attention to the role of invariance. Schlick allowed (contra Hertz) that uniquely correct models of the world are possible (Schlick 1920, 85–6), and may be put in direct coincidence with external causal relations, motivating a stronger conception of realism than Helmholtz himself accepted (Friedman 1997). In contrast, Cassirer emphasized throughout his work the key role of invariance, and that all that can be extracted from the world on the structuralist viewpoint are its invariant relations (Cassirer 1923 [1910]; Lovrenov 2006), a perspective he would later reapply to perception itself (Cassirer 1944 [1938]). While Schlick's transmission of a transformed, logico-centric *Zeichentheorie* to the Vienna Circle resulted in a fruitful, but ultimately brittle research program, Cassirer's more abstract invariance-based approach lay fallow, only recently rediscovered and reclaimed by contemporary structural realists (e.g. French 2014).

These final reflections indicate a possible role for the Doctrine in contemporary philosophy of science. For today's structural realisms are embroiled in a number of internecine disputes, concerning especially the question of the nature of the map between theory and world, and the ontological question of what exactly a structuralist should be realist about (Frigg 2006; Frigg and Votsis 2011; McKenzie 2017). Many of the details of this debate are rooted in a post-Positivist concern for fundamental physics and mathematized philosophy, yet philosophy of science as a whole has become more ecumenical, turning attention to biology and the social sciences as equally legitimate examples of scientific inquiry. Sensory physiology, and the epistemological reflections arising from the Doctrine, deserves acknowledgment and study as an exemplar of structuralist reasoning in an area other than physics, one which proved fruitful

[20]Schlick was instrumental in promoting Helmholtz's importance as a philosopher through editing the 1921 centenary collection of his epistemological writings, and cites him in key works. Cassirer gives Helmholtz pride of place as the culmination of a long trend toward structuralism in the latter chapters of his 1923 [1910] *Substance and Function*.

in inspiring the structuralist perspective in the first place. If today's structuralists turn their attentions past physics to the sciences beyond, it may yet prove inspirational again.

5 Conclusion: *Realism without Tears*

Müller's Doctrine of Specific Nerve Energies implies a skeptical conclusion: our sensory experience does not reveal the nature of its causes, nor does it provide us with any direct access to basic properties in the world. He derives this conclusion from incontrovertible empirical results and three methodological principles. Since these principles have become enshrined in the contemporary science of perception, grounding the study of the neurophysiology, psychology, and psychophysics of perception, this skeptical conclusion remains an unequivocal part of the naturalistic worldview.

Nevertheless, naturalists need not be global skeptics. Müller, Helmholtz, and others who reflected on the Doctrine chose instead to embrace *epistemic structural realism*, the view that structural relations between simple perceptual properties may convey knowledge of structural features in the world. Recent emphasis on embodied action as part of the mechanism by which perceptual content is determined does not constitute a radical break with Helmholtz and the Doctrine, but instead escapes skepticism through essentially the same route: active exploration produces patterns in our sensory experience that may ground our knowledge of relations in the world. Likewise, the weak naturalist who takes conscious perceptual experience to be epistemically direct, in the sense that it requires no further justification, builds her epistemology on firmer ground if she accepts its structural relations as epistemically primitive, rather than the simple qualities with which the Doctrine is concerned.

Philosophy of Science is less beholden to the Doctrine. Today's structural realists rarely ground their epistemology in that of perception, though historically their roots trace back to Müller, since he influenced Helmholtz, du Bois-Reymond, and Mach, who in turn influenced Hertz, Cassirer, and Schlick, and through them both neo-Kantians and Logical Positivists. Nevetheless, the very questions in the epistemology of geometry that reinforced for Helmholtz a close analogy between perception and science divorced science from the epistemology of perception with the rise of General Relativity. Still, contemporary structural realists have lessons to learn from early perceptual structuralism, for instance, the value of invariance.

Sensory physiology undermines the naïve view that perceptual experience puts us into direct contact with the world, but it suggests a more tempered realism to replace it. This realism rests our knowledge of the world not on pre-established harmony, nor favorable statistics, but our own exploratory activity, experiment, and engagement with the world. It is a realism for active epistemic agents, and as such, realism both easy and enough.

References

Akins, Kathleen (1996). "Of Sensory Systems and the "Aboutness" of Mental States". In: *Journal of Philosophy* 93 (7), pp. 337–372.

Akins, Kathleen A. and Martin Hahn (2014). "More than Mere Colouring: The Role of Spectral Information in Human Vision". In: *British Journal for Philosophy of Science* 65, pp. 125–171.

Allen, Keith (2016). *A Naïve Realist Theory of Colour*. Oxford: Oxford UP.

Banks, Erik (2000). "Ernst Mach's World Elements: A Study in Natural Philosophy". PhD thesis. City University of New York.

Barwich, Ann-Sophie (2018). "Measuring the World: Olfaction as a Process Model of Perception". In: *Everything Flows: Towards a Processual Philosophy of Biology*. Ed. by D. Nicholson and J. Dupré. Oxford UP, pp. 337–356.

Bois-Reymond, Emil du (1874). "The Limits of Our Knowledge of Nature". In: *Popular Science Monthly* 5, pp. 17–32.

Brading, Katherine and Elise Crull (2017). "Epistemic Structural Realism and Poincaré's Philosophy of Science". In: *HOPOS* 7, 108–129Fr.

Bruineberg, Jelle, Julian Kiverstein, and Erik Rietveld (2016). "The anticipating brain is not a scientist: the free-energy principle from an ecological-enactive perspective". In: *Synthese*. ISSN: 1573-0964. DOI: 10.1007/s11229-016-1239-1. URL: https://doi.org/10.1007/s11229-016-1239-1.

Cassirer, Ernst (1923 [1910]). *Substance and Function & Einstein's Theory of Relativity*. Trans. by William Curtis Swabey and Marie Collins Swabey. New York: Dover.

— (1944 [1938]). "The Concept of Group and the Theory of Perception". Trans. by A. Gurwitsch. In: *Philosophy and Phenomenological Research* 5, pp. 1–35.

— (1950). *The Problem of Knowledge: Philosophy, Science, and History Since Hegel*. Trans. by William H. Woglom and Charles W. Hendel. New Haven, CT: Yale UP.

Chakravartty, Anjan (2001). "The Semantic or Model-Theoretic View of Theories and Scientific Realism". In: *Synthese* 127.3, pp. 325–345.

Chemero, Anthony (2009). *Radical Embodied Cognitive Science*. MIT Press.

Clark, Andy (2016). *Surfing Uncertainty: Prediction, Action, and the Embodied Mind*. Oxford UP.

— (2017a). "Busting Out: Predictive Brains, Embodied Minds, and the Puzzle of the Evidentiary Veil". In: *Noûs* 51 (4), pp. 727–753.

— (2017b). "How to Knit Your Own Markov Blanket:" in: *Philosophy and Predictive Processing*. Ed. by Thomas K. Metzinger and Wanja Wiese. Frankfurt am Main: MIND Group. Chap. 3. ISBN: 9783958573031. DOI: 10.15502/9783958573031. URL: https://predictive-mind.net/papers/how-to-knit-your-own-markov-blanket.

Clark, Austen (1993). *Sensory Qualities*. Oxford: Clarendon Press.

Crane, Tim and Craig French (2017). "The Problem of Perception". In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Spring 2017. Metaphysics Research Lab, Stanford University.

Daston, Lorraine and Peter Galison (2010). *Objectivity*. New York: Zone Books.

Drayson, Zoe (2017). "Direct Perception and the Predictive Mind". In: *Philosophical Studies*. URL: https://doi.org/10.1007/s11098-017-0999-x.

Duffy, Charles J. and Robert H. Wurtz (1991). "Sensitivity of MST Neurons to Optic Flow Stimuli. II. Mechanisms of Response Selectivity Revealed by Small-Field Stimuli". In: *Journal of Neurophysiology* 65 (6), pp. 1346–1359.

Fairchild, Mark D. (2005). *Color Appearance Models*. 2nd ed. Chichester, West Sussex: John Wiley & Sons, Ltd.

French, Steven (2014). *The Structure of the World*. Oxford: Oxford University Press.

Friedman, Michael (1997). "Helmholtz's *Zeichentheorie* and Slick's *Allgemeine Erkenntnislehre*: Early Logical Empiricism and Its Nineteenth-Century Background". In: *Philosophical Topics* 25, pp. 19–50.

Frigg, Roman (2006). “Scientific Representation and the Semantic View of Theories”. In: *Theoria* 55, pp. 49–65.

Frigg, Roman and Ioannis Votsis (2011). “Everything You Always Wanted to Know about Structural Realism but were Afraid to Ask”. In: *European Journal for Philosophy of Science* 1, pp. 227–276.

Gehringer, William L. and Edward Engel (1986). “Effect of Ecological Viewing Conditions on the Ames’ Distorted Room Illusion”. In: *Journal of Experimental Psychology: Human Perception and Performance* 12 (2), pp. 181–185.

Genone, James (2016). “Recent Work on Naïve Realism”. In: *American Philosophical Quarterly* 53.1, pp. 1–25.

Gibson, James J. (1960). “The Concept of the Stimulus in Psychology”. In: *The American Psychologist* 15, pp. 694–703.

— (1966). *The Senses Considered as Perceptual Systems*. Boston, MA: Houghton Mifflin Co.

— (1986). *The Ecological Approach to Visual Perception*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Gower, Barry (2000). “Cassirer, Schlick and ‘Structural’ Realism: The Philosophy of the Exact Sciences in the Background to Early Logical Empiricism”. In: *British Journal for the History of Philosophy* 8, pp. 71–106.

Grind, W. A. van de (1990). “Smart Mechanisms for the Visual Evaluation and Control of Self-Motion”. In: *Perception and Control of Self Motion*. Ed. by Rik Warren and Alexander H. Wertheim. Psychology Press, pp. 357–398.

Hamlyn, D. W. (1977). “Unconscious Inference and Judgment in Perception”. In: *Images, Perception, and Knowledge*. Ed. by John M. Nicholas. Springer, pp. 195–212.

Hatfield, Gary (1990). *The Natural and the Normative*. Cambridge, MA: MIT Press.

— (2002). “Perception as Unconscious Inference”. In: *Perception and the Physical World: Psychology and Philosophical Issues in Perception*. Ed. by Dieter Heyer and Rainer Mausfeld. John Wiley & Sons, Ltd., pp. 247–254.

— (2011). “Kant and Helmholtz on Primary and Secondary Qualities”. In: *Primary and Secondary Qualities: The Historical and Ongoing Debate*. Ed. by Lawrence Nolan. Oxford UP, pp. 304–338.

— (2018). “Helmholtz and Philosophy”. In: *Journal for the History of Analytical Philosophy* 6.3, pp. 12–41.

Helmholtz, Hermann von (1962 [1910]). *Helmholtz’s Treatise on Physiological Optics*. Ed. by James P. C. Southall. 3rd. Vol. 3. New York, NY: Dover Publications, Inc.

— (1971 [1847]). “The Conservation of Force: A Physical Memoir”. In: *Selected Writings of Hermann von Helmholtz*. Ed. by Russell Kahl. Middletown, CT: Wesleyan University Press, pp. 3–55.

— (1971 [1894]). “Introduction to the Lectures on Theoretical Physics”. In: *Selected Writings of Hermann von Helmholtz*. Ed. by Russell Kahl. Middletown, CT: Wesleyan University Press, pp. 513–529.

— (1977 [1868]). “On the Origin and Significance of the Axioms of Geometry”. In: *Epistemological Writings*. Ed. by R. S. Cohen and Y. Elkana. Boston Studies in the Philosophy of Science, vol. XXXVII. Dordrecht, Holland: D. Reidel, pp. 1–38.

— (1977 [1878]). “The Facts in Perception”. In: *Epistemological Writings*. Ed. by R. S. Cohen and Y. Elkana. Boston Studies in the Philosophy of Science, vol. XXXVII. Dordrecht, Holland: D. Reidel, pp. 115–185.

— (1995 [1869]). "On the Aim and Progress of Physical Science". In: *Science and Culture: Popular and Philosophical Writings*. Ed. by David Cahan. Chicago University Press, pp. 204–225.

Hering, Ewald (1913). *Memory: Lectures on the Specific Energies of the Nervous System*. 4th. address delivered 1870, Vienna. Chicago: Open Court.

Hertz, Heinrich (1899). *The Principles of Mechanics*. Trans. by D. E. Jones and J. T. Walley. New York: Macmillan and Co.

Hilbert, David (2012). "Constancy, Content, and Inference". In: *Visual Experience: Sensation, Cognition, and Constancy*. Ed. by Gary Hatfield and Sarah Allred. Oxford UP, pp. 199–211.

Hohwy, Jakob (2016). "The Self-Evidencing Brain". In: *Noûs* 50 (2), pp. 259–285.

— (2017). "How to Entrain Your Evil Demon". In: *Philosophy and Predictive Processing*. Ed. by Thomas K. Metzinger and Wanja Wiese. Frankfurt am Main: MIND Group. Chap. 2. ISBN: 9783958573048. DOI: `10.15502/9783958573048`. URL: `https://predictive-mind.net/papers/how-to-entrain-your-evil-demon`.

Howson, Colin and Peter Urbach (2006). *Scientific Reasoning: The Bayesian Approach*. 3rd. Peru, Il: Open Court.

Isaac, Alistair M. C. (2013). "Quantifying the Subjective: Psychophysics and the Geometry of Color". In: *Philosophical Psychology* 26 (2), pp. 207–233.

— (2017). "Hubris to humility: Tonal volume and the fundamentality of psychophysical quantities". In: *Studies in History and Philosophy of Science Part A* 65-66. The Making of Measurement, pp. 99 –111. ISSN: 0039-3681. DOI: `https://doi.org/10.1016/j.shpsa.2017.06.003`. URL: `http://www.sciencedirect.com/science/article/pii/S0039368117301589`.

— (2018). "Prospects for Timbre Physicalism". In: *Philosophical Studies* 175, pp. 503–529.

Jeffrey, Richard (1965). *The Logic of Decision*. University of Chicago Press.

Kaplan, Mark (2002). "The Very Idea of Perception as a Process of Unconscious Probabilistic Inference". In: *Perception and the Physical World: Psychology and Philosophical Issues in Perception*. Ed. by Dieter Heyer and Rainer Mausfeld. John Wiley & Sons, Ltd., pp. 115–143.

Knill, David C. and Whitman Richards, eds. (1996). *Perception as Bayesian Inference*. Cambridge University Press.

Kock, Liesbet De (2014a). "Hermann von Helmholtz's Empirico-Transcendentalism Reconsidered: Construction and Constitution in Helmholtz's Psychology of the Oject". In: *Science in Context* 27.4, pp. 709–744.

— (2014b). "In the Beginning was the Act: A Historical and Systematic Analysis of Hermann von Helmholtz's Psychology of the Object". PhD thesis. Universiteit Gent.

— (2018). "Historicizing Hermann von Helmholtz's Psychology of Differentiation". In: *Journal for the History of Analytical Philosophy* 6.3, pp. 42–62.

Köhler, Wolfgang (1971 [1913]). "On Unnoticed Sensations and Errors of Judgment". In: *The Selected Papers of Wolfgang Köhler*. Ed. by Mary Henle. Trans. by Helmut E. Adler. New York: Liveright, pp. 13–39.

Ladyman, James (1998). "What is Structural Realism?" In: *Studies in History and Philosophy of Science* 29, pp. 409–424.

— (2016). "Structural Realism". In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Winter 2016. Metaphysics Research Lab, Stanford University.

Lenoir, Timothy (2006). "Operationalizing Kant: Manifolds, Models, and Mathematics in Helmholtz's Theories of Perception". In: *The Kantian Legacy in Nineteenth-Century Science*. Ed. by Michael Friedman and Alfred Nordmann. Cambridge, MA: MIT Press, pp. 141–210.

Leroux, Jean (2001). "“Picture Theories” as Forerunners of the Semantic Approach to Scientific Theories". In: *International Studies in the Philosophy of Science* 15.2, pp. 189–197.

Lier, Rob van, Mark Vergeer, and Stuart Anstis (2009). "Filling-in afterimage colors between the lines". In: *Current Biology* 19.8, R323 –R324. ISSN: 0960-9822. DOI: `https://doi.org/10.1016/j.cub.2009.03.010`. URL: `http://www.sciencedirect.com/science/article/pii/S0960982209008112`.

Lovrenov, Maja (2006). "The Role of Invariance in Cassirer's Interpretation of the Theory of Relativity". In: *Synthesis Philosophica* 42, pp. 233–241.

Lyons, Jack (2017). "Epistemological Problems of Perception". In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Spring 2017. Metaphysics Research Lab, Stanford University.

Mach, Ernst (1896 [1885]). *Contributions to the Analysis of the Sensations*. Trans. by C. M. Williams. La Salle, IL: Open Court.

Mattens, Filip (2017). "The Sense of Touch: From Tactility to Tactual Probing". In: *Australasian Journal of Philosophy* 95.4, pp. 688–701. DOI: `10.1080/00048402.2016.1263870`. eprint: `https://doi.org/10.1080/00048402.2016.1263870`. URL: `https://doi.org/10.1080/00048402.2016.1263870`.

McDonald, Patrick J. (2002). "Helmholtz's Methodology of Sensory Science, The *Zeichentheorie*, and Physical Models of Hearing Mechanisms". In: *History of Philosophy of Science: New Trends and Perspectives*. Ed. by Michael Heidelberge and Friedrich Stadler. Netherlands: Kluwer, pp. 159–183.

McKenzie, Kerry (2017). "Ontic Structural Realism". In: *Philosophy Compass* 12, pp. 1–11.

Moulines, Carlos-Ulises (1981). "Hermann von Helmholtz: A Physiological Approach to the Theory of Knowledge". In: *Epistemological and Social Problems of the Sciences in the Early Nineteenth Century*. Ed. by H. N. Jahnke and M. Otte. Dordrecht, Holland: D. Reidel, pp. 65–73.

Müller, Johannes Peter (1833 / 1840). *Handbuch der Physiologie des Menschen*. 2 volumes, Trans. by Baly as *Elements of Physiology* (Taylor and Walton, 1838 / 1842). Coblenz: J. Hölscher.

Noë, Alva (2004). *Action in Perception*. Cambridge, MA: MIT Press.

Patton, Lydia (2009). "Signs, Toy Models, and the A Priori: From Helmholtz to Wittgenstein". In: *Studies in History and Philosophy of Science* 40, pp. 281–289.

Peirce, Charles Sanders (1955 [1883]). "The General Theory of Probable Inference". In: *Philosophical Writings of Peirce*. Ed. by Justus Buchler. Dover, pp. 190–217.

— (1955 [c.1902]). "Perceptual Judgments". In: *Philosophical Writings of Peirce*. Ed. by Justus Buchler. Dover, pp. 302–305.

Poincaré, Henri (1958 [1905]). *The Value of Science*.

Psillos, Stathis (2001). "Is Structural Realism Possible?" In: *Philosophy of Science* 68.3, S13–S24.

Rock, Irvin (1983). "Inference in Perception". In: *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association, 1982, vol. 2*, pp. 525–540.

Runeson, Sverker (1977). "On the Possibility of “Smart” Perceptual Mechanisms". In: *Scandinavian Journal of Psychology* 18, pp. 172–179.

— (1988). "The Distorted Room Illusion, Equivalent Configuration, and the Specificity of Static Optic Arrays". In: *Journal of Experimental Psychology: Human Perception and Performance* 14 (2), pp. 295–304.

Ryckman, T. A. (1991). "*Conditio Sine Qua Non*? *Zuordnung* in the Early Epistemologies of Cassirer and Schlick". In: *Synthese* 88, pp. 57–95.

Schiemann, Gregor (1998). "The Loss of World in the Image: Origin and Development of the Concept of Image in the Thought of Hermann von Helmholtz and Heinrich Hertz". In: *Heinrich Hertz: Classical Physicist, Modern Philosophy*. Ed. by Davis Baird, R. I. G. Hughes, and Alfred Nordmann. Boston Studies in the Philosophy of Science, vol. 198. Dordrecht, Holland: D. Reidel, pp. 25–38.

Schlick, Moritz (1920). *Space and Time in Contemporary Physics: An Introduction to the Theory of Relativity and Gravitation*. Trans. by Henry L. Brose. New York: Oxford University Press.

Shepard, Roger N. (1981). "Psychophysical Complementarity". In: *Perceptual Organization*. Ed. by Kubovy and Pomerantz. Lawrence Erlbaum, pp. 279–341.

Shimony, Abner (1970). "Scientific Inference". In: *The Nature and Function of Scientific Theories*. Ed. by Robert G. Colodny. University of Pittsburgh Press, pp. 79–172.

Stevens, S. S. (1975). *Psychophysics*. New York: John Wiley & Sons.

Suppe, Frederick (1977). *The Structure of Scientific Theories*. Urbana, IL: university of Illinois Press.

Suppes, Patrick (2002). *Representation and Invariance of Scientific Structures*. Stanford, CA: CSLI Publications.

Tye, Michael (2014). "Transparency, Qualia Realism, and Representationalism". In: *Philosophical Studies* 170, pp. 39–57.

van Fraassen, Bas (1980). *The Scientific Image*. Oxford: Oxford University Press.

Wagner, Mark (2006). *The Geometries of Visual Space*. Mahwah, NJ: Lawrence Erlbaum Associates.

Wolff, Johanna (2012). "Do Objects Depend on Structures?" In: *British Journal for Philosophy of Science* 63 (3), pp. 607–625.